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Abstract

The Earth Radiation Budget Experiment (ERBE) instruments are designed to measure the components of the radiative exchange between the Sun, Earth and space. ERBE is comprised of three spacecraft, each carrying a nearly identical set of radiometers: a three-channel narrow-field-of-view scanner, a two-channel wide-field-of-view (limb-to-limb) non-scanning radiometer, a two-channel medium field-of-view (~1000 km) non-scanning radiometer, and a solar monitor. Ground testing showed the scanners to be susceptible to self-generated and externally generated electromagnetic noise. This paper describes the pre-launch corrective measures taken and the post-launch corrections to the NOAA-9 scanner data. The NOAA-9 scanner has met the mission objectives in accuracy and precision, in part because of the pre-launch reductions of and post-launch data corrections for the electromagnetic noise.

Introduction

The Earth Radiation Budget Experiment (ERBE) instrument package is comprised of a three-channel narrow-field-of-view scanner, a two-channel wide-field-of-view (limb-to-limb) non-scanner radiometer, a two-channel medium field-of-view (~1000 km) non-scanner radiometer, and a solar monitor. The non-scanning instruments and the solar monitor are described by *Luther* et al. [1986] and the scanning instruments by *Kopia* [1986]. The ERBE radiometers were built and tested by TRW.

A description of the ERBE data products and a brief synopsis of ERBE's scientific results are given by *Barkstrom* et al. [1989]. The ERBE scanner ground and in-flight calibration are described by *Lee* et al. [1989].

The ERBE scanners met the mission objectives for accuracy and precision. This success was due, in part, to critical corrective measures taken to solve problems with noise in the data. During a ground calibration of the ERBE National Oceanic and Atmospheric Administration (NOAA) NOAA-9 scanner, excessive data noise was observed, which was due to improper electronic design and packaging. The noise was primarily caused by self-generated electromagnetic interference (EMI). This was evidenced by the scan-to-scan repeatability of the noise versus scan position profile, that is, the noise was largely synchronous with the scan period. Subsequent analysis of the noise resulted in hardware corrections which reduced the self-EMI or "offset noise" by a factor of 2 to 4.

The NOAA-9 scanner was selected as the test bed for the offset reduction efforts, as it originally was scheduled to be the first of the three to fly. (The Earth Radiation Budget Satellite (ERBS) scanner was actually the first.) The three scanners did not all have the same set of hardware corrective measures applied. Electronic design changes were made to the ERBS and NOAA-10 scanners (but not the NOAA-9) involving low pass filtering of the digital to analog converter inputs and high-frequency filtering of the voltage and signal lines.

Cost and schedule constraints severely limited the scope of pre-flight corrective programs. Ultimately, the offsets were accounted for in the processing of in-orbit data. This paper describes the procedures used to evaluate the offsets in flight.

Instruments and Operations

The ERBE scanner spectral bands are 0.2 to 5 μm (shortwave), 5 to 50 μm (longwave), and <0.2 to >200 μm (total). Solar reflected radiance leaving the Earth-atmosphere system is sampled by the shortwave and the total channels. Earth-atmosphere emitted radiance is sampled by the total and longwave channels. The redundancy in the estimations of the two radiance wavebands provided by the three channels is a valuable tool for instrument diagnostics.

Usually, the scanners sweep limb-to-limb normal to the satellite ground track. In some situations, the scan plane is rotated slightly to avoid imaging the Sun on the detectors.

One set of ERBE instruments was launched on ERBS in October 1984 from the space shuttle Challenger into a nearly circular 610-km altitude orbit at 57° inclination. The second ERBE instrument set was launched aboard the NOAA satellite NOAA-9 in December 1984 into a nearly circular 864-km altitude orbit at a nearly Sun-synchronous 99° inclination. The third set, aboard NOAA-10, was launched September 17, 1986, into a nearly circular 826-km altitude orbit at a nearly Sun-synchronous 99° inclination. The ERBS spacecraft, in contrast to the Sun-synchronous spacecraft, precesses in local time of equatorial crossings by 20 minutes per day, thus enhancing diurnal sampling for the monthly averaged data products. On January 1, 1987, the NOAA-9 and NOAA-10 spacecraft local times of ascending node were 2:55 p.m. and 7:26 p.m.., respectively.

To avoid contamination associated with launch, the instrument covers were kept closed for the first several weeks in orbit. Earth-viewing scanner science observations by ERBS began on November 5, 1984, and by NOAA-9 on February 1, 1985. The NOAA-10 scanner began science observations on October 24, 1986. However, an erroneous scanner azimuth reading occurred on NOAA-10 on November 12 and the instrument was stowed from November 18 to December 5. The azimuth reading anomaly was thought to be caused by sunlight leaking into the azimuth position optical encoder. Because of uncertainties in the scanner azimuth position, the scanner was placed in the stow position to guard against scanning the Sun until the anomaly could be diagnosed. The NOAA-9 scanner operated successfully until January 20, 1987. The NOAA-10 scanner continued to transmit science data until May 22, 1989. The ERBS scanner operated over 5 years (until February 28, 1990). All three ERBE scanners either met or exceeded the design lifetime of 2 years. All of the ERBE non-scanning instruments, including the solar monitors, are still operational.

In ground testing, the NOAA-9 and NOAA-10 scanners were found to be susceptible to *external* as well as internal sources of EMI. Both the NOAA-9 scanner and non-scanner showed a sensitivity to the Search and Rescue beacon adjacent to the scanner instrument on the spacecraft. The cause of this sensitivity to the transmitted signal is not well understood, but the effect appeared to be stable and was accounted for in the course of in-flight offset noise characterization. Fortunately, the Search and Rescue beacons operated continuously in orbit, rather than intermittently. There is no Search and Rescue beacon on the ERBS spacecraft.

The ERBS spacecraft was pitched over 180° to allow the scanner to view space over all normally Earth-viewing positions so that the offsets could be measured. This was done twice. The NOAA spacecraft were not similarly rotated because of requirements of other experiments.

IN-ORBIT OFFSET CORRECTION PROCEDURES

The first ERBS pitch-over to the space view occurred November 21, 1984, and scanner offsets were derived. A second ERBS pitch-over to space on October 19, 1985, showed that the total and longwave channel offsets had not changed appreciably from the first to the second pitch-over on October 19, 1985 {*Halyo* et al., 1989; *Paden* et al., 1991}. An experimental effort to compare NOAA-9 and ERBS nighttime scanner mean radiances showed that the pre-launch derived offsets for the NOAA-9 total and longwave channels were not acceptable for data processing. (The NOAA-9 shortwave channel offsets were evaluated by observations of the dark side of the Earth.) The "latitude band" method, as it was called, restricted the latitudes of the radiance comparisons such that the local times of the measurements of the two scanners approximately matched to reduce sensitivity to diurnal effects. The measurements were compared at essentially matching viewing zenith angles at night so that no limb darkening models were required (except for the assumption of azimuthal symmetry).

In April 1986, the "clear tropical ocean" method for NOAA-9 offset correction was evaluated. The essential idea was to find, via ERBS, nighttime clear-sky tropical (30° S. to

30°N.) ocean scenes that are highly uniform in longwave outgoing flux density, and use them as calibration targets for NOAA-9. These targets are "calibrated" by the ERBS scanner. The centers of the pixels of the two scanners were required to be within 0.15° Earth central angle of each other. The clear-sky tropical ocean scenes are believed to have negligible overnight diurnal variations in outgoing longwave flux density. The results suffered from an artifact in the ERBS scanner, "striping," which was evident in the maps of clear-sky tropical oceans produced by the ERBS scanner.

The striping phenomenon was manifested by alternating high/low measurements with a principal period of 32 seconds or 8 scans. The cause was traced to fluctuations in the space-clamp zero reference, which then corrupted the entire scan. Additional studies led to an algorithm for stripe removal that used the internal calibration (at the opposite end of the scan from the space-clamp) for the zero reference computation when the space-clamp measurement set behaved in a certain well-defined suspicious manner. The NOAA-9 scanner did not exhibit striping.

With the striping problem solved, the way appeared to be clear to production of ERBS scanner radiances, which were to be used in determination of the NOAA-9 scanner offsets. The ERBE Science Team had designated the months of April, July, October 1985, and January 1986 as the first priority for NOAA-9 data processing. These NOAA-9 months, together with the same ERBS months, constitute the "validation months," as they offer multiple satellite data spanning the seasons of a year.

APRIL 1985 OFFSET CORRECTION

In late 1986, a set of offset corrections was proposed for the NOAA-9 scanner for April 1985. The shortwave channel offsets were estimated by observations of the dark side of the Earth by NOAA-9. The longwave and total channel offsets were based on analyses of 4 days by the "clear tropical ocean" (CTO) method and of 1 day by the "latitude band method" (LBM). The latitude band analysis was employed because the CTO method did not produce results for all Earth-viewing scan angles. Both methods were briefly described in the preceding section. The next section describes the LBM in more detail.

Latitude Band Method (LBM)

The LBM is comprised of the following three steps:

(1) The ERBS and NOAA-9 longwave and total channel nighttime (pixel solar zenith angle $\geq 100°$) measurements are compared over the same latitude band. The data day(s) of the month and the latitude band are chosen to closely match local time sampling. For April 1985, the chosen day was April 7 and the latitude band was 12.15° N. to 32.15° N. There is a trade-off between latitude band width and local time matching; the wider the band, the more sampling, but the greater the range of local time differences between the two scanner's measurements. The range of local time matching is illustrated in Figure 1.

(2) The measurements are averaged over all nighttime passes through the latitude band at each scan angle. The averaging is stratified by orbital passes and 5° latitude bins as a hedge against non-uniform sampling. (The bulk of the sampling non-uniformity is caused by data failing various edit checks.) Since the two spacecraft were at different altitudes, there was no precise match of viewing zenith angles (the angle from the target zenith to the spacecraft). The ERBS measurements were quadratically interpolated to the nearest viewing zenith angle position of NOAA-9. Since the measurements at this point had not been corrected for imperfect optical transmission, a differential spectral correction

(on the order of 1%) was made to the ERBS measurements, that is, the ERBS optically filtered measurements were converted into equivalent NOAA-9 filtered measurements to account for differences in the absorptances of the black painted thermistor bolometer flakes.

(3) The NOAA-9 offset corrections were estimated as the ERBS processed mean measurements minus the NOAA-9 mean measurements.

Clear Tropical Ocean Method (CTO)

The CTO method consists of three steps:

(1) The nighttime (pixel solar zenith angle ≥ 100°) "clear tropical oceans" ERBS pixels are selected by the ERBE scene identification algorithm operating on ERBS scanner measurements.

(2) For each 3-by-3 pixel array centered on each "clear tropical ocean" ERBS pixel, the central pixel is rejected unless:

(a) the ERBS outgoing longwave flux densities, the filtered longwave channel measurements, and the filtered total channel measurements all pass the standard edit checks;

(b) the "maximum influence" (explained in the Appendix) of the "vector gradient" of the outgoing longwave flux density is less than 4.35 W m^{-2} (1.5% of a CTO scene at 290 W m^{-2}) at the Earth central angle of radius 0.15° centered at the central pixel;

(c) the "maximum influence" (explained in the Appendix) of the "second derivative" matrix of the outgoing longwave flux density is less than 4.35 W m^{-2} at the Earth central angle of radius 0.15° centered at the central pixel;

(d) the central pixel is more than 100 km from all ERBS pixels rejected by any of the preceding criteria; and

(e) the central pixel is more than 200 km from land.

Each nighttime (pixel solar zenith angle ≥ 100°) NOAA-9 pixel is rejected unless:

(a) it is more than 100 km from all rejected ERBS pixels;

(b) it is more than 200 km from land, (to avoid land-breeze-generated cloud development);

(c) it is within 0.15° (or 0.25° when sampling was significantly improved thereby) Earth central angle of an accepted ERBS pixel (termed a "neighboring" ERBS pixel); and

(d) its viewing zenith angle is sufficiently close to that of a "neighboring" ERBS pixel that a conservative estimate of uncertainty in the limb darkening correction of the ERBS measurement (explained in the following) is less than ±1.5%. These ERBS measurements are referred to as "paired" measurements.

(3) For each accepted NOAA-9 pixel, all "paired" ERBS pixels longwave and total channel measurements are adjusted by the differential spectral correction as in the LBM and by a limb darkening model derived from ERBS crosstrack observations of clear tropical oceans. The NOAA-9 offsets for the day at each NOAA-9 scan angle position are estimated as the average difference of the "paired" measurements, adjusted ERBS minus NOAA-9.

The "conservative estimate of uncertainty" in the limb darkening assumes spectral radiance models generated by using TIROS Operational Vertical Sounder (TOVS) atmosphere soundings [*Avis* et al., 1984]. The 48 models for tropical ocean, clear sky and overcast, each at four viewing zenith angles, are used for the uncertainty estimate. The overcast models (24, each at four viewing zenith angles) are included to ensure that estimates of the limb darkening error estimates are conservative. The limb darkening uncertainty is estimated as plus or minus one-half the range of the tropical ocean model limb darkening, clear sky, and overcast, the effect of which was to constrain the range of pairings of NOAA-9 and ERBS viewing zenith angles as in Figure 2. In principle, Figure 2 should have symmetry about the 45° line. The 15° resolution in NOAA-9 viewing zenith angles causes the minimum ERBS viewing zenith angle curve to miss the abscissa value of 37°, marked by a diamond in the figure. This had a conservative effect. Figure 2 reflects the observation that the slopes of limb darkening functions are less scene-dependent near nadir than at higher viewing zenith angles.

The actual limb darkening correction is founded on ERBS measurements of large areas of tropical ocean identified as clear and of locally uniform flux density. Large-scale nonuniformities were of concern, which led to the constraints on the range of pairings of ERBS and NOAA-9 viewing zenith angles following from the "conservative estimate of uncertainty" in limb darkening correction. Far superior limb darkening models have recently been derived [Smith et al., 1989; 1990] from ERBE measurements taken while scanning along-track (in the orbit plane) where single sites are viewed at a wide range of viewing zenith angles in a short period of time. The limb darkening corrections used in NOAA-9 offset determination result in negligible errors, ~ +/- 0.1%, relative to the along-track models.

April 1985 Offset Determination Results

The CTO method did not yield results for all Earth-viewing scan angle positions for any of the 4 days examined. Of the 56 Earth-viewing scan angle positions of NOAA-9, CTO analyses produced results for the following:

Date	No. of Total Channel Positions	No. of Longwave Channel Positions
April 7	39	32
April 13	44	44
April 21	40	40
April 25	25	25

Furthermore, some scan angle position offsets were not found by CTO analyses for any day. The Latitude Band Method, employed to complement the CTO method, produced offsets over all Earth-viewing scan positions for April 7.

The total and longwave channel offsets for the month were estimated as the means of the 4-day set of offsets, with the April 7 set the mean of the CTO and LBM sets. The standard errors in the estimates of the mean (over the 4 days) offset profiles are ± 0.51 for the total channel and ± 0.59 for the longwave channel in unfiltered (corrected for optical transmission losses) units, W m^{-2}-sr^{-1}. (The standard errors were computed only over scan positions having CTO-derived offsets.) The standard error, ε, for each channel, longwave and total, was computed as:

$$\varepsilon = \sqrt{\sum_{d=1}^{4}\left\{\frac{1}{n_d}\sum_{i=1}^{n_d}\left[\frac{1}{m_i-1}\left(x_{i,d}-\overline{x_i}\right)^2\right]\right\}}$$

where $\overline{x_i}$ is the mean offset over the 4 days at the scan position labeled i, $x_{i,d}$ is the CTO-derived offset for day d at position i, n_d is the number of scan positions having CTO-derived offsets for day d, and m_i is the number of days for which offsets at scan position i are estimated.

The shortwave channel offsets were also determined by averaging the offsets over the 4 days. The root-mean-square (over scan position) standard error in the mean (over the 4 days) shortwave offsets is ±.08 W m^{-2}-sr^{-1} unfiltered.

Before incorporation in the archived April 1985 data sets, these offsets were adjusted to account for changes in all the ERBS scanner gain coefficients arising from reexamination of ground calibration data and instrument characterization. These adjustments had no effect on the standard error estimates.

July 1985 Offset Correction

During the determination of the April 1985 offsets, it became obvious that the CTO method was too labor-intensive and time-consuming to be used in operational data processing. In September 1987, ERBS scanner filtered radiance data were produced for July 1985 by the ERBE Data Processing Team, clearing the way for determination of the offsets for the second NOAA-9 validation month. The following December, a new offset estimation method, the "latitude-local time binning" (LLTB) method, was applied to the NOAA-9 scanner for July 1985. LLTB was an outgrowth and refinement of the LBM. (The shortwave channel offsets were found by NOAA-9 observations of the dark Earth.) With the LBM, there is a trade-off between latitude band width and local time matching; the wider the band, the more sampling, but the greater the range of local time differences between the two scanner's measurements. The LLTB removes the latitude band restriction by allowing the measurements at each viewing zenith angle to be compared at any matching latitude and local time, resulting in an increase in sampling for the same local time matching criterion.

Latitude-Local Time Binning Method

The Latitude-Local Time Binning Method is a six step process.

(1) For each scan position, the ERBS and NOAA-9 filtered longwave and total channel nighttime measurements over a 24-hour period are sorted into 2° latitude by 1-hour local time bins.

(2) An ERBS bin is considered full when it has at least 80 measurements for either channel; the NOAA-9 bins required only 70 since the NOAA-9 data processing drops every eighth scan line because of electromagnetic interference from a data buffer.

(3) The ERBS bin means are adjusted by the usual differential spectral correction.

(4) Steps (1) - (3) are repeated with a half-hour shift in the local time boundaries, and only the "better" sampling is accepted for each NOAA-9 scan position and channel. The "better" sampling is that which maximizes

$$\frac{1}{\dfrac{1}{N_{vlt}}+\dfrac{1}{E_{v'lt}}}$$

where N_{vlt} is the number of NOAA-9 measurements for each channel at scan position v, latitude bin l, and local time bin t; and $E_{v'lt}$ is the corresponding ERBS quantity at scan position v'.The scan positions v and v' correspond to nearly equal viewing zenith angles. The "better" sampling criterion assumes equal and uncorrelated meteorological "noise" variance for the two scanners at the given viewing zenith angle and latitude and local time bins.

(5) The ERBS bin means are quadratically interpolated over three successive scan positions to match with the NOAA-9 viewing zenith angles and latitude-local time bins.

(6) The NOAA-9 filtered offset correction estimates for the day are computed as the mean differences between the ERBS and NOAA-9 filled matching bin means.

For the July 1985 longwave and total offsets, 13 days of ERBS and NOAA-9 data were used. There were clearly discernible differences in the offset corrections from the first half of the month to the second. The period, July 1 - 16 was represented by 6 days, July 6, 8, 12, 13, 15, and 16, while the remainder of the month was represented by 7 days, July 19, 21, 22, 23, 27, 28, and 30.

ERBE inversion of radiances to flux densities rejects viewing zenith angles greater than 70° because of the unreliability of the models of the angular directionality of outgoing radiation at large viewing zenith angles and because the footprint is oversized. For viewing zenith angles less than or equal to 70°, the mean (over scan position) one-sigma formal estimates of errors in the mean (over time) offsets in unfiltered radiance units for both longwave and total channels are ± 0.6 and ± 0.4 W m^{-2}-sr^{-1} for the first and last halves of July, respectively. These error estimates, ε, were computed as:

$$\varepsilon = \frac{\sum_{j=8}^{57} \left\{ \sqrt{\sum_{d=1}^{N_d} \left[\frac{\left(x_{j,d} - \langle x_j \rangle \right)^2}{N_d (N_d - 1)} \right]} \right\}}{57 - 8 + 1}$$

where j is the scan position, N_d is the number of data days used, d is the data day label, $x_{j,d}$ is the offset correction at scan position j and data day d, and $\langle x_j \rangle$ is the mean of $x_{j,d}$ over the data days. The range of scan positions 8 through 57 contains the viewing zenith angles less than or equal to 70°.

Some ERBS data days are not usable in offset estimation. When the ERBS orbit was entirely sunlit, or nearly so, there were very little, if any, nighttime data covering all Earth-viewing scan positions. When the ERBS/NOAA-9 nighttime local times match at latitudes near 57° in either hemisphere, poor matched sampling results. The ERBS orbit inclination is 57°, and that of NOAA 9 is-99°. Near 57° latitude, the two spacecraft are moving at approximately right angles to each other. While a small change in local time translates to a large change in latitude for NOAA-9, the opposite is true for ERBS under these conditions. Also, on some days, the ERBS data suggest a possible offset problem for ERBS, and these data days were rejected as a precaution.

The potential ERBS offset inaccuracies were checked by binning up over each candidate day the nighttime longwave and total channel measurements into 2° latitude bins over selected latitude ranges for ERBS on either the ascending or descending portion of the orbit. The ERBS precesses only 20 minutes in local time per day, allowing the latitude ranges to be selected so that several days in succession can be examined over the same latitude range and in the same ascending/descending mode. The specification of ascending/descending mode prevented large local time differences day to day at a given latitude; the choice was made such that the latitude range in darkness was maximized. The means of the latitude bin means as functions of the Earth-viewing scan positions were examined for signs of offset inaccuracies--unevenness and large day-to-day variations of the functions.

The July 1985 shortwave channel offsets were derived from the 29 days with NOAA-9 data. The mean one-sigma error in the time-averaged offsets in unfiltered radiance units is ± 0.03 W m^{-2}-sr^{-1}. The error was computed as for the total and longwave channels, except that the range of scan positions was 5 to 60, encompassing all Earth-viewing positions.

The Last Offset Correction Procedure

Although the Latitude-Local Time Binning method as implemented for July 1985 is less labor-intensive than the CTO method, the improvement was not enough to satisfy the demands of the coming data archive production schedule. Further, there was the deepening suspicion that the NOAA-9 offsets frequently change significantly over periods much shorter than a month. On February 9, 1988, the offsets were determined for the third validation month, October 1985, by application of a modified version of latitude-local time binning which addresses both the labor intensity and offset volatility concerns.

The new method does not require that the offsets are invariant over at least several days, but assumes that offset-corrected nighttime radiance functions of scan position averaged over a given broad latitude band are constant over the month. The mean *uncorrected* nighttime radiance functions are computed in the same manner as those of ERBS in the ERBS offset check with 2° latitude bins. It follows that the difference in the mean uncorrected measurements at a given scan position between any 2 days is the corresponding difference in the offset. Then, in principle, the daily offsets can be found by finding the offsets for a single day of the month and differencing that day's corrected measurement profile with the uncorrected profiles of the other days of the month (i.e., uncorrected minus corrected). In practice, two or more NOAA-9 days' longwave and total offsets are usually determined in order to minimize meteorological related variations (~ 1 W-m^{-2}-sr^{-1} for 1 day) by the Latitude-Local Time method. The resulting offset-corrected nighttime radiance profiles were averaged to produce the monthly (assumed) invariant radiance functions of scan position. Occasionally, the radiance profiles were somewhat noisy in appearance and were modified by application of one of two rather gentle smoothing filters, illustrated in Figure 3.

Figure 4 illustrates the results of the above procedure applied to December 1985 NOAA-9 offset determination. The ordinate is in unfiltered radiance, where "unfiltered" means that the non-ideal spectral throughput of the NOAA-9 total channel has been taken into account. The scan positions on the abscissa are those for which the viewing zenith angles are less than 70° and thus represent candidates for inversion of radiances to flux densities. The two dashed curves are the NOAA-9 radiance profiles for 2 days before offset correction. The two curves with solid lines and plotting symbols are the radiance profiles after application of the 1 day's offset determination, and the solid line curve without plotting symbols is the five-point smoothed mean.

The stability of the latitudinally averaged radiance profiles is illustrated in Figure 5, where NOAA-9 mean total channel filtered radiances, *not in-orbit offset-corrected*, binned into 5° latitude bins over a 40° latitude range for April 4 and 17, 1985, are plotted. The assumed offsets in the data processing code were the same for the 2 days and were derived from ground testing. The filtered radiances are converted into unfiltered by multiplying by 1.098.

In addition to the latitude binning test of ERBS, another check was imposed on the ERBS scanner. The "scanner/non-scanner comparison at satellite altitude," [Green et al. ,1989] converted nighttime scanner total channel measurements to "equivalent" non-scanner total channel measurements by a summation procedure. The longwave channel was not similarly checked because it was weighted only slightly in the unfiltering of radiances and the scanner/non-scanner comparison simulations are computer-intensive.

The last offset correction procedure sped up the process enough to keep pace with the other data processing activities. By September 1989, 15 months of NOAA-9 offsets had been completed, February 1985 through February 1986 and October and December 1986. October 1986 was of special interest because it coincided with Project FIRE (First ISCCP [International Satellite Cloud Climatology Project Regional Experiment]), and December 1986 because it coincided with the first continuous NOAA-10 science data. The offset correction procedure has been modified for application to the NOAA-10 scanner.

The offset correction procedure has now been further automated to speed up the process. By October 1990, the NOAA-9 offsets had been determined for all scanner months.

Figures 6, 7, and 8 are time lines of the estimated NOAA-9 offsets at scan position 33 (near nadir) for the three channels. Some indication of the variation of the April 1985 (the first "validation" month) offsets about the time-averaged (over 4 days) mean can be gleaned from the day-to-day variations in March and May 1985. The June 1985 offsets are similarly informative about the July 1985 (the second "validation" month) offsets. August 1985 is a special case; on August 3, the scan plane was rotated in azimuth to the along-track scanning position where it remained until August 9; no data are available for August 1 or 2. The along-track data for the total and longwave channels suggest that these channel offsets are scan-plane dependent, as was indicated by pre-flight testing.

December 1986 is also a special case. The first try at offset estimation assumed that a single set of offsets for each channel would suffice for the month, or failing that, that only a few would be needed. At issue was a trade-off between offset accuracy and data processing expense. The preliminary monthly offsets were those derived for December 19. After the accuracy/expense trade-off was evaluated, 11 additional days were reprocessed with new offsets derived for each of these days, December 1-7 and December 9, 10, 30, and 31. The remaining days in December retained the December 19 offset estimates. The reprocessing reduced the maximum estimated (for viewing zenith angles less than 70°) offset error magnitude over the month in the total channel from 2.5 to 1.5 W m^{-2}-sr^{-1} unfiltered. With the exception of 1 day, the shortwave channel offsets did not enter into the trade-off, as their variations are relatively small. Figure 9 illustrates the problem. The cost in computer resources used to rerun a single day is $4,000. By rerunning 10 days, as the plot shows, the maximum estimated offset error magnitude would be reduced to 1.5 W m^{-2}-sr^{-1}. One extra day, December 9, was rerun to correct the (appreciable) shortwave offsets (as well as the total and longwave channel offsets).

At the time of the December 1986 offset determination, filtered radiances were offset-corrected in the production of data tapes ("pre-PATs") used as *input* to the processing of the daily science *output* products (PATs, or Processed Archival Tapes) containing filtered radiances, unfiltered radiances, scene identifications, top-of-the-atmosphere flux densities, etc. Thus, the pre-PAT for any day requiring offset correction was processed twice, once for evaluating offsets and once to supply corrected input to PAT production. It is the reprocessing of the pre-PAT that costs about $4000. This situation was a consequence of the prevailing doctrine that the pre-PAT would be the repository of fully calibrated and corrected instrument data. In January 1989, it was proposed that the implementation of the NOAA-9 offset corrections be transferred to the processing of the PATs, forming the "single pass system," which eliminated the need to reprocess pre-PATs. The "single pass system" was exercised on NOAA-9 for about 14 months and 19 days of data. Assuming 28 data days per month to allow for telemetry outages, the savings realized by the new "system" amount to over $ 1.6 million. The "single pass system" also saved 3 to 4 working days of processing time per month, which totals to 44 to 59 working days of processing time for NOAA-9.

Concluding Remarks

Ground testing showed the ERBE scanners to be susceptible to self-generated and externally generated electromagnetic noise. Pre-launch corrective measures were taken, but the NOAA-9 and NOAA-10 scanners still exhibited unacceptable offset noise levels.

Instrument analysts successfully applied innovative post-launch calibration methods to reduce ERBE scanner errors to levels which met all science requirements. Significant improvements and refinements in the correction methods have resulted in accurate, reliable, automated procedures which ensured timely, efficient processing of the ERBE data.

Appendix

The following describes the calculation of the "maximum influence of the gradient" of the outgoing longwave flux density and the "maximum influence of the second derivative matrix of the outgoing longwave flux density." Limits were placed on these quantities for the purpose of identifying scenes highly uniform in longwave flux density.

Consider a 3x3 array of ERBS pixels. The central pixel is indexed (i, j), where i refers to displacements in the scan direction and j, in the ground track direction. The coordinate axes thus defined are very nearly orthogonal. For any given array, the first index runs i-1, i, i+1 and the second index runs j-1, j, j+1. The Earth is considered to be locally flat over the array.

Latitudes over the array are denoted as $LAT_{i,j}$; longitudes, $LONG_{i,j}$; and outgoing longwave flux densities, $LW_{i,j}$, etc.

The gradient of longwave flux density in the scan direction is

$$grad_s = \left(LW_{i+1,j} - LW_{i-1,j}\right) \div \Delta ECAs_{i,j}$$

where $\Delta ECAs_{i,j}$ is the Earth central angle from (i-1, j) to (i+1, j).

The gradient in the ground track direction is

$$grad_g = \left(LW_{i,j+1} - LW_{i,j-1}\right) \div \Delta ECAg_{i,j}$$

where $\Delta ECAg_{i,j}$ is the Earth central angle from (i, j-1) to (i, j+1).

The magnitude of the total gradient is

$$grad = \sqrt{grad_s^2 + grad_g^2}$$

The "maximum influence of the gradient" at the circle of radius 0.15° Earth central angle centered at the central pixel of the array is grad x 0.15 W/m^2.

For computing the "second derivative matrix of the outgoing longwave flux density," the following Earth central angles are approximated by

$$ECA_{(i-1,j-1),(i,j-1)} = \sqrt{\left(LAT_{i,j-1} - LAT_{i-1,j-1}\right)^2 + \cos\left(LAT_{i,j}\right)\left(LONG_{i,j-1} - LONG_{i-1,j-1}\right)^2}$$

$$ECA_{(i,j-1),(i+1,j-1)} = \sqrt{\left(LAT_{i+1,j-1} - LAT_{i,j-1}\right)^2 + \cos\left(LAT_{i,j}\right)\left(LONG_{i+1,j-1} - LONG_{i,j-1}\right)^2}$$

$$ECA_{(i-1,j),(i,j)} = \sqrt{\left(LAT_{i,j} - LAT_{i-1,j}\right)^2 + \cos\left(LAT_{i,j}\right)\left(LONG_{i,j} - LONG_{i-1,j}\right)^2}$$

$$ECA_{(i,j),(i+1,j)} = \sqrt{\left(LAT_{i+1,j} - LAT_{i,j}\right)^2 + \cos\left(LAT_{i,j}\right)\left(LONG_{i+1,j} - LONG_{i,j}\right)^2}$$

$$ECA_{(i-1,j+1),(i,j+1)} = \sqrt{\left(LAT_{i,j+1} - LAT_{i-1,j+1}\right)^2 + \cos\left(LAT_{i,j}\right)\left(LONG_{i,j+1} - LONG_{i-1,j+1}\right)^2}$$

$$ECA_{(i,j+1),(i+1,j+1)} = \sqrt{\left(LAT_{i+1,j+1} - LAT_{i,j+1}\right)^2 + \cos\left(LAT_{i,j}\right)\left(LONG_{i+1,j+1} - LONG_{i,j+1}\right)^2}$$

$$ECA_{(i-1,j-1),(i-1,j)} = \sqrt{\left(LAT_{i-1,j} - LAT_{i-1,j-1}\right)^2 + \cos\left(LAT_{i,j}\right)\left(LONG_{i-1,j} - LONG_{i-1,j-1}\right)^2}$$

$$ECA_{(i,j-1),(i,j)} = \sqrt{\left(LAT_{i,j} - LAT_{i,j-1}\right)^2 + \cos\left(LAT_{i,j}\right)\left(LONG_{i,j} - LONG_{i,j-1}\right)^2}$$
$$ECA_{(i+1,j-1),(i+1,j)} = \sqrt{\left(LAT_{i+1,j} - LAT_{i+1,j-1}\right)^2 + \cos\left(LAT_{i,j}\right)\left(LONG_{i+1,j} - LONG_{i+1,j-1}\right)^2}$$
$$ECA_{(i-1,j),(i-1,j+1)} = \sqrt{\left(LAT_{i-1,j+1} - LAT_{i-1,j}\right)^2 + \cos\left(LAT_{i,j}\right)\left(LONG_{i-1,j+1} - LONG_{i-1,j}\right)^2}$$
$$ECA_{(i,j),(i,j+1)} = \sqrt{\left(LAT_{i,j+1} - LAT_{i,j}\right)^2 + \cos\left(LAT_{i,j}\right)\left(LONG_{i,j+1} - LONG_{i,j}\right)^2}$$
$$ECA_{(i+1,j),(i+1,j+1)} = \sqrt{\left(LAT_{i+1,j+1} - LAT_{i+1,j}\right)^2 + \cos\left(LAT_{i,j}\right)\left(LONG_{i+1,j+1} - LONG_{i+1,j}\right)^2}$$

where $ECA_{(i-1,j-1),(i,j-1)}$ is the Earth central angle from pixel (i-1, j-1) to pixel (i, j-1), etc.

The second derivative matrix of the outgoing longwave flux density,

$$\begin{bmatrix} \Phi_{11} & \Phi_{12} \\ \Phi_{21} & \Phi_{22} \end{bmatrix}$$

where the "1" direction is along the scan and the "2" direction is along the ground track, is approximated as follows:

$$\Phi_{11} = \frac{\left(LW_{i+1,j} - LW_{i,j}\right) / ECA_{(i,j),(i+1,j)} - \left(LW_{i,j} - LW_{i-1,j}\right) / ECA_{(i-1,j),(i,j)}}{\frac{1}{2}\left(ECA_{(i,j),(i+1,j)} + ECA_{(i-1,j),(i,j)}\right)}$$

$$\Phi_{22} = \frac{\left(LW_{i,j+1} - LW_{i,j}\right) / ECA_{(i,j),(i,j+1)} - \left(LW_{i,j} - LW_{i,j-1}\right) / ECA_{(i,j-1),(i,j)}}{\frac{1}{2}\left(ECA_{(i,j),(i,j+1)} + ECA_{(i,j-1),(i,j)}\right)}$$

$$\Phi_{12} = \Phi_{21} = \tfrac{1}{2}\left(\Phi'_{12} + \Phi'_{21}\right)$$

where

$$\Phi'_{12} = \frac{\left(\dfrac{LW_{i+1,j+1} - LW_{i+1,j-1}}{ECA_{(i+1,j),(i+1,j+1)} + ECA_{(i+1,j-1),(i+1,j)}}\right) - \left(\dfrac{LW_{i-1,j+1} - LW_{i-1,j-1}}{ECA_{(i-1,j),(i-1,j+1)} + ECA_{(i-1,j-1),(i-1,j)}}\right)}{ECA_{(i,j),(i+1,j)} + ECA_{(i-1,j),(i,j)}}$$

$$\Phi'_{21} = \frac{\left(\dfrac{LW_{i+1,j+1} - LW_{i-1,j+1}}{ECA_{(i,j+1),(i+1,j+1)} + ECA_{(i-1,j+1),(i,j+1)}}\right) - \left(\dfrac{LW_{i+1,j-1} - LW_{i-1,j-1}}{ECA_{(i,j-1),(i+1,j-1)} + ECA_{(i-1,j-1),(i,j-1)}}\right)}{ECA_{(i,j),(i,j+1)} + ECA_{(i,j-1),(i,j)}}$$

The second derivative matrix is diagonalized via a coordinate rotation by solving

$$\begin{vmatrix} \Phi_{11}-\lambda & \Phi_{12} \\ \Phi_{12} & \Phi_{22}-\lambda \end{vmatrix} = 0$$

The central pixel of the array is rejected if the magnitude of either of the two solutions for λ, the second derivatives in the rotated system, exceeds

$$\frac{2\langle LW\rangle\delta}{(\Delta r)^2}$$

where $\langle LW\rangle$ is a representative value, 290 W-m^{-2} , for the longwave flux density outgoing from clear tropical ocean scenes at the "top of the atmosphere;" δ is the threshold fraction of $\langle LW\rangle$, 0.015; and Δr is the Earth central angle, 0.15°,(from the central pixel) at which the influence of the second derivative matrix is considered.

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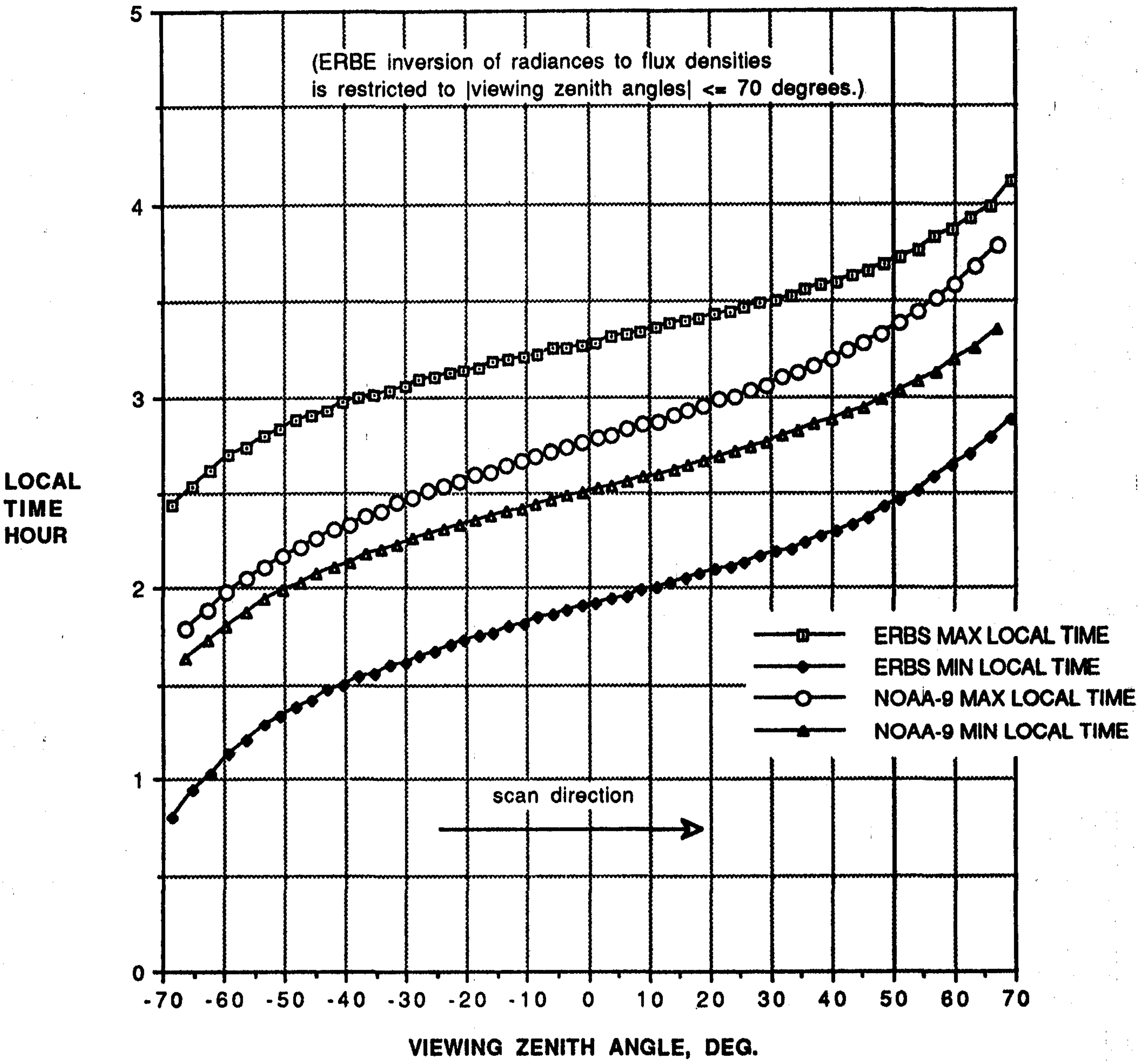

Figure 1.- ERBS and NOAA-9 Local Time Sampling Latitude Band Method for April 7, 1985 Over Latitude Range 12.15 North to 32.15 North

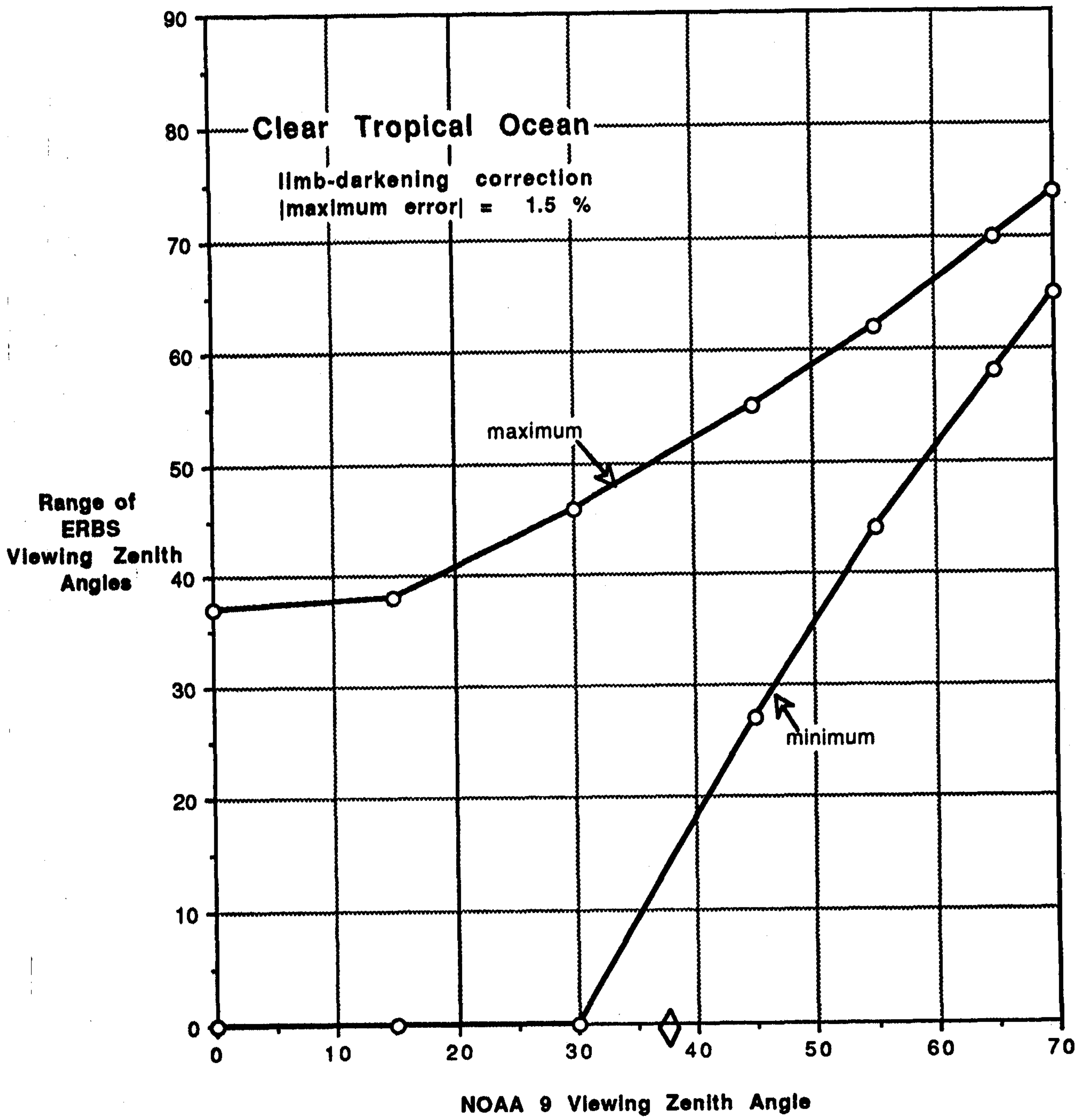

Figure 2.- ERBS & NOAA 9 Viewing Zenith Angles for Pixel Pairing

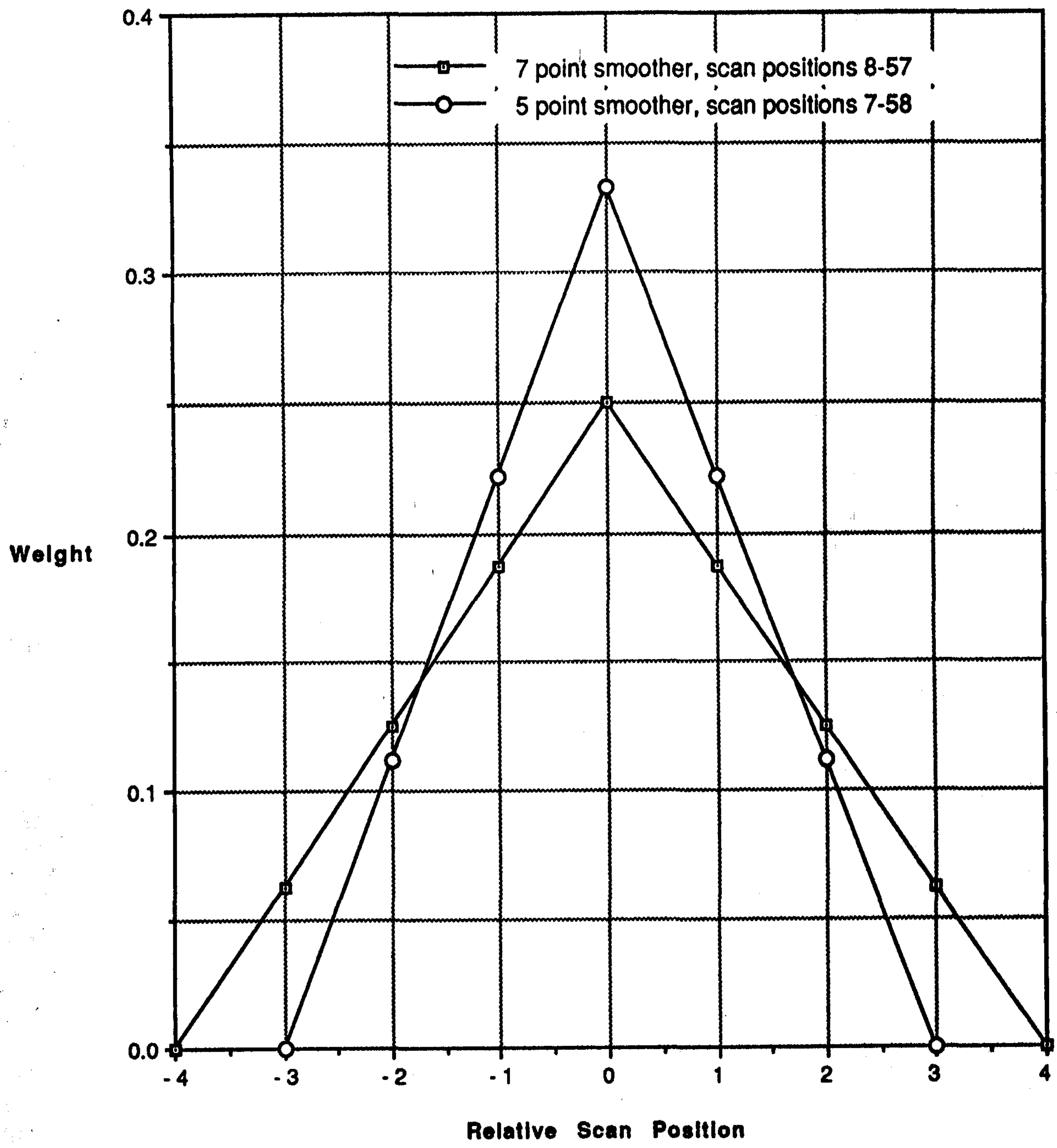

Figure 3.- Five and Seven-Point Smoothers

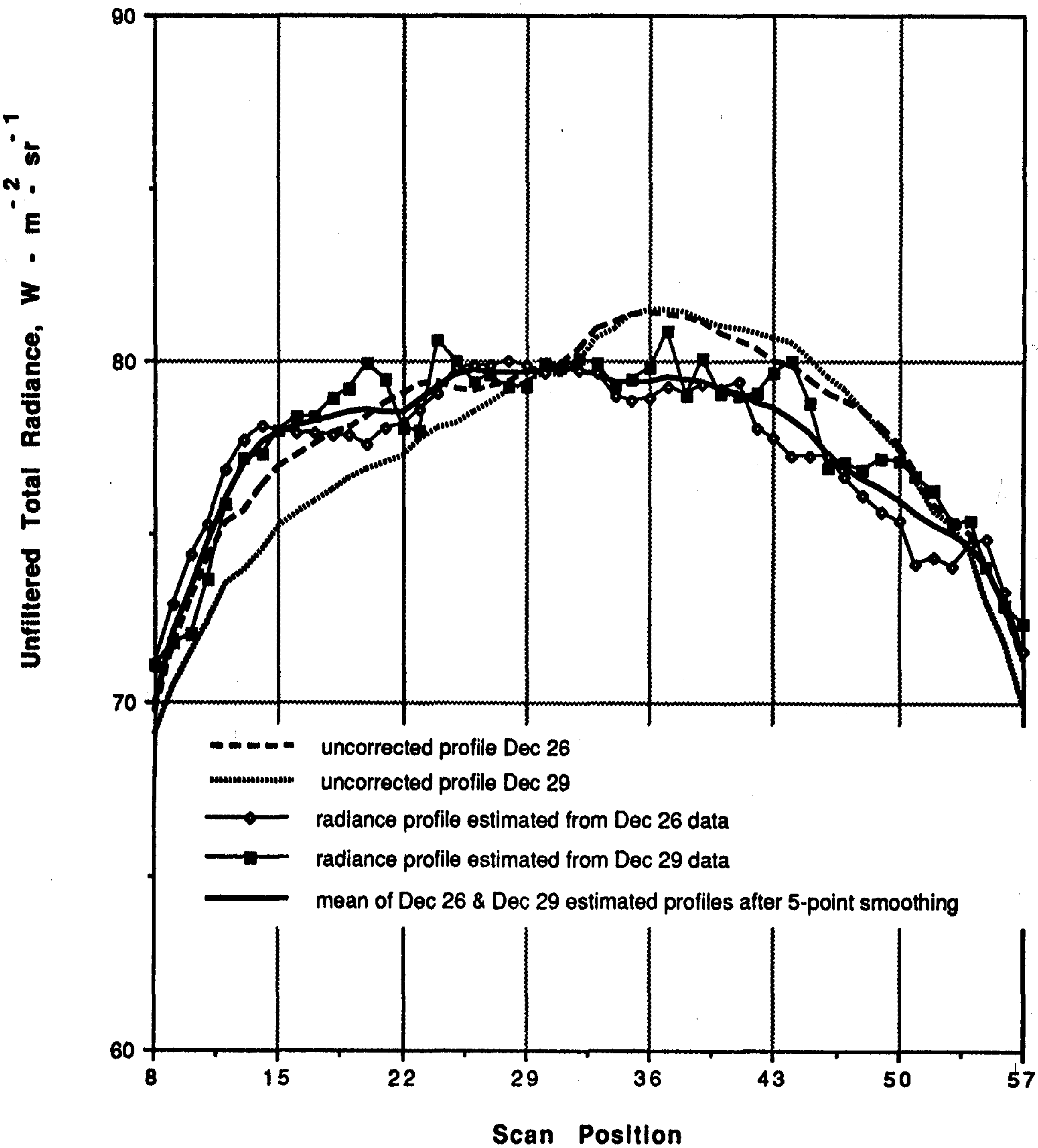

Figure 4.- **Estimates of Invariant Radiance Profiles for NOAA 9 Dec'85 (Nighttime) over Latitudes 35S to 55N**

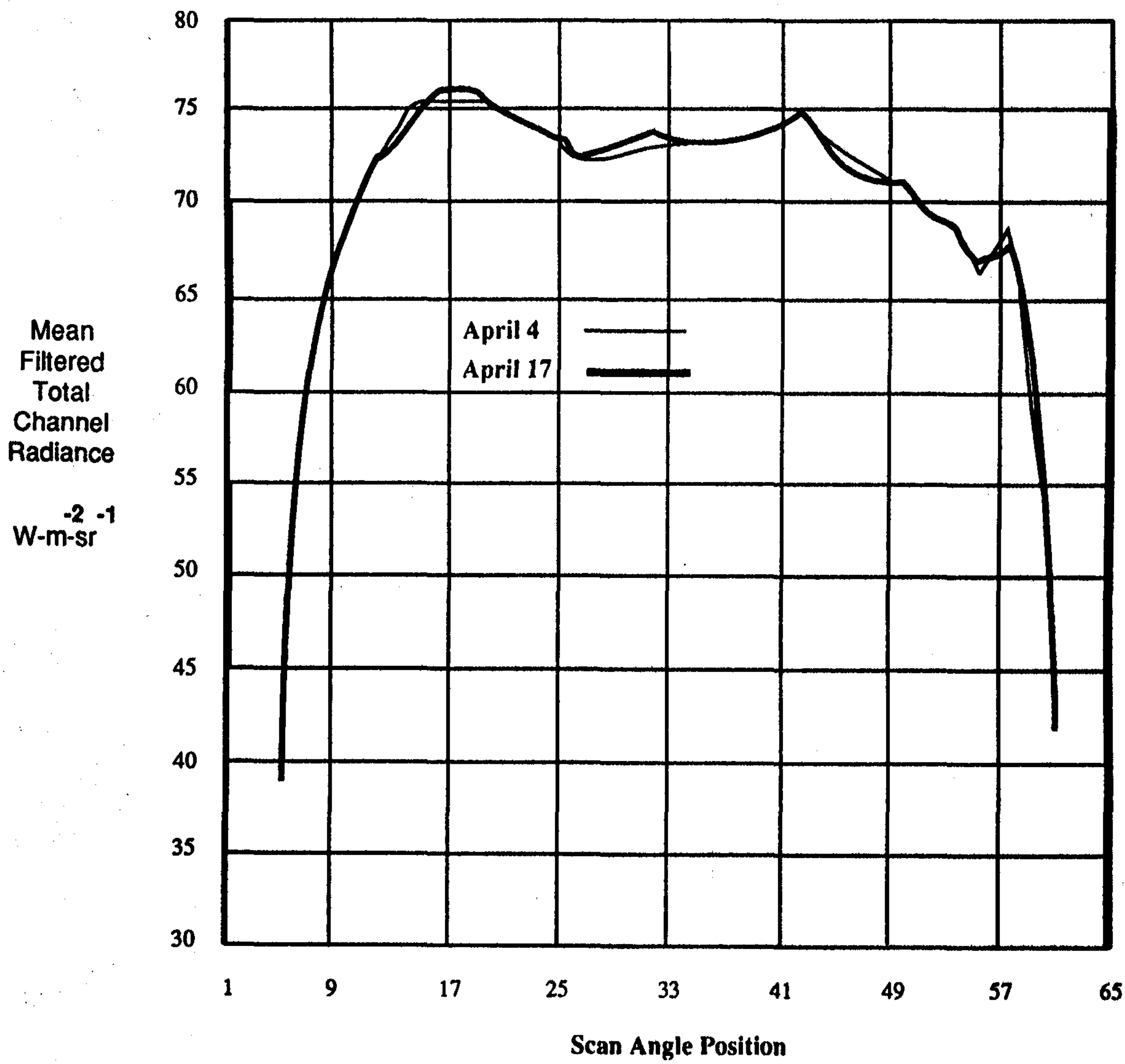

Figure 5.- NOAA-9 Total Channel Mean Nighttime Measurements over Latitudes 20S to 20N for April 4 & 17, 1985 before Offset Correction

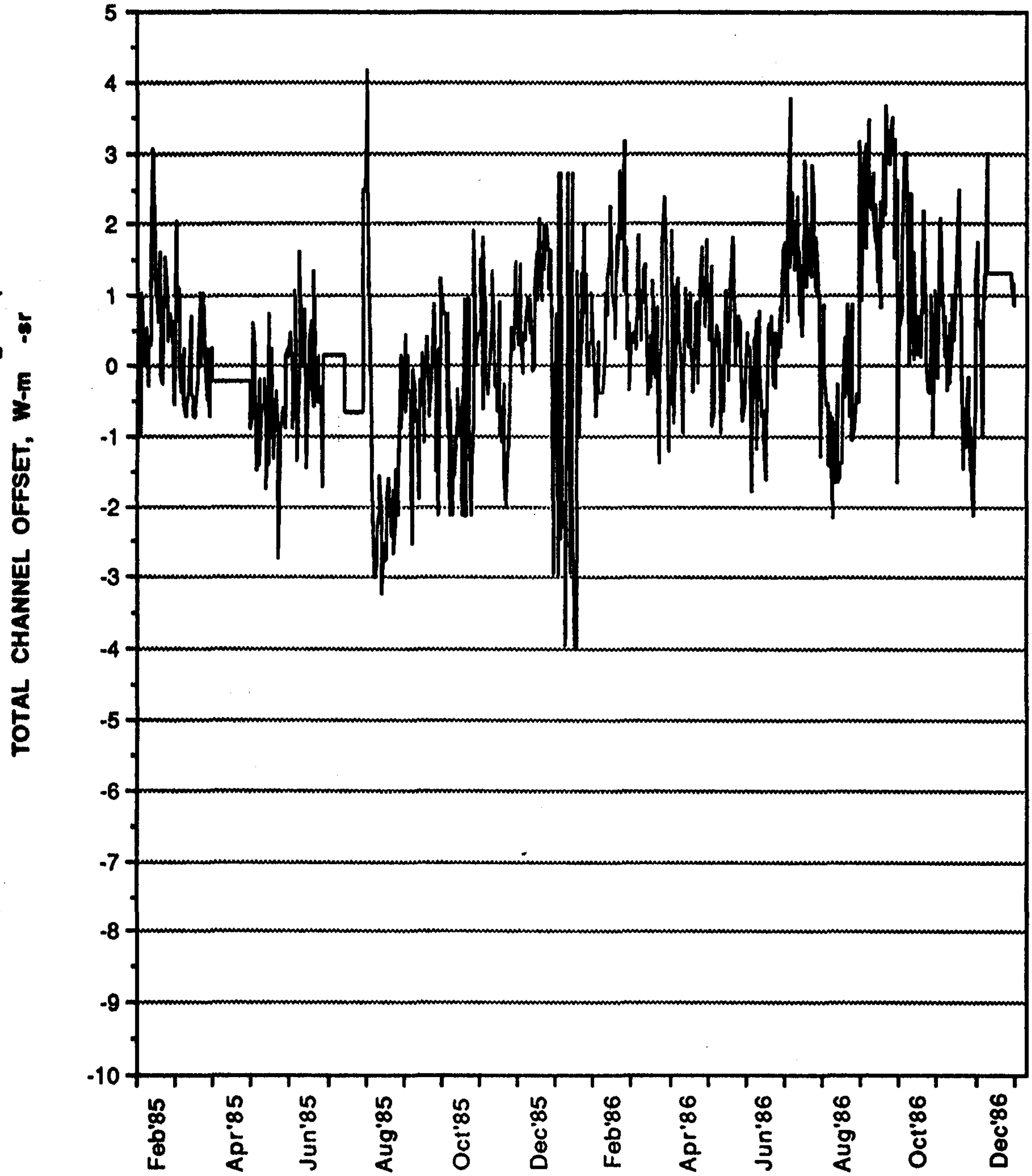

FIGURE 6.- NOAA-9 TOTAL CHANNEL UNFILTERED OFFSETS NEAR THE NADIR SCAN POSITION

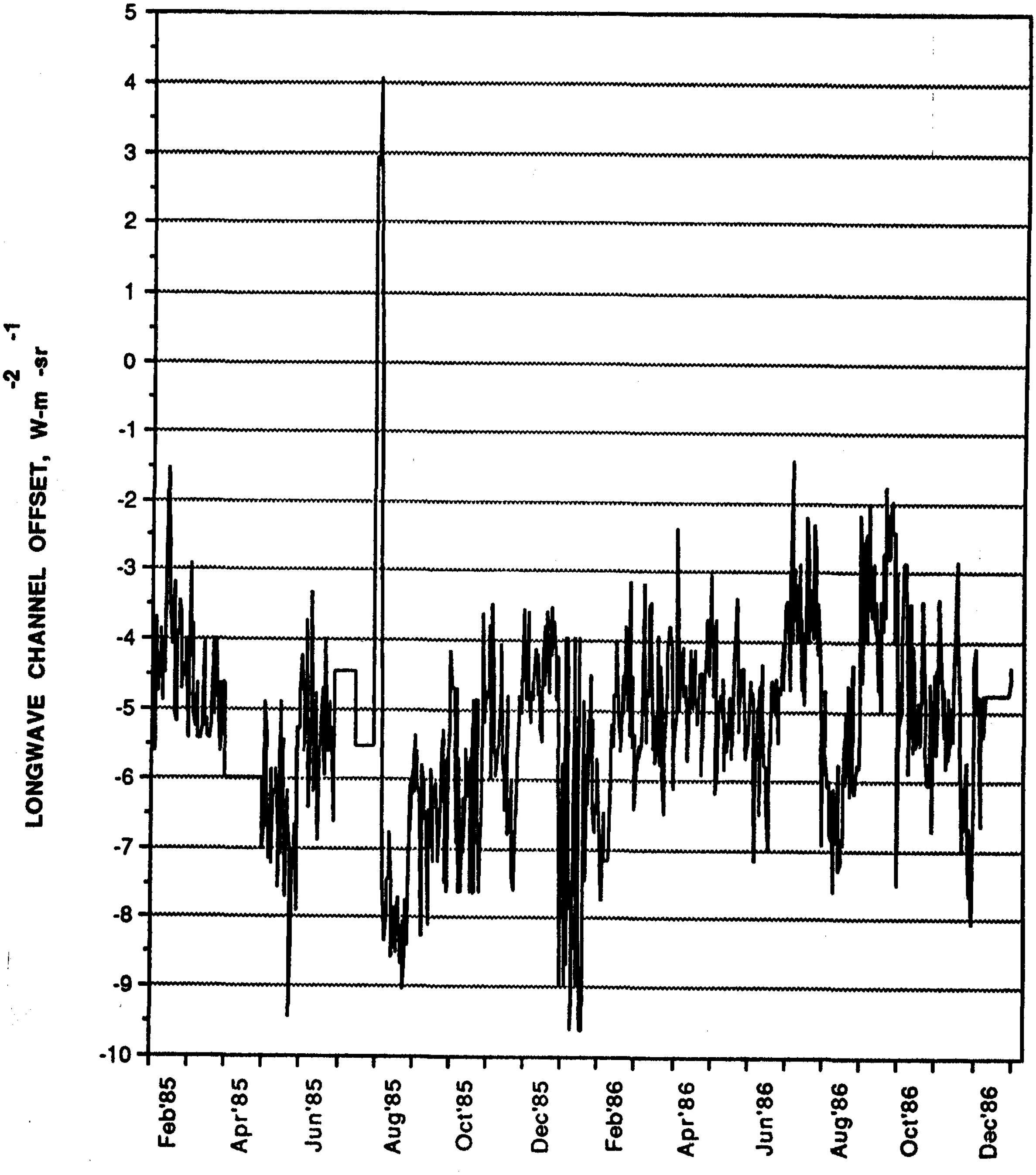

FIGURE 7.- NOAA-9 LONGWAVE CHANNEL UNFILTERED OFFSETS NEAR THE NADIR SCAN POSITION

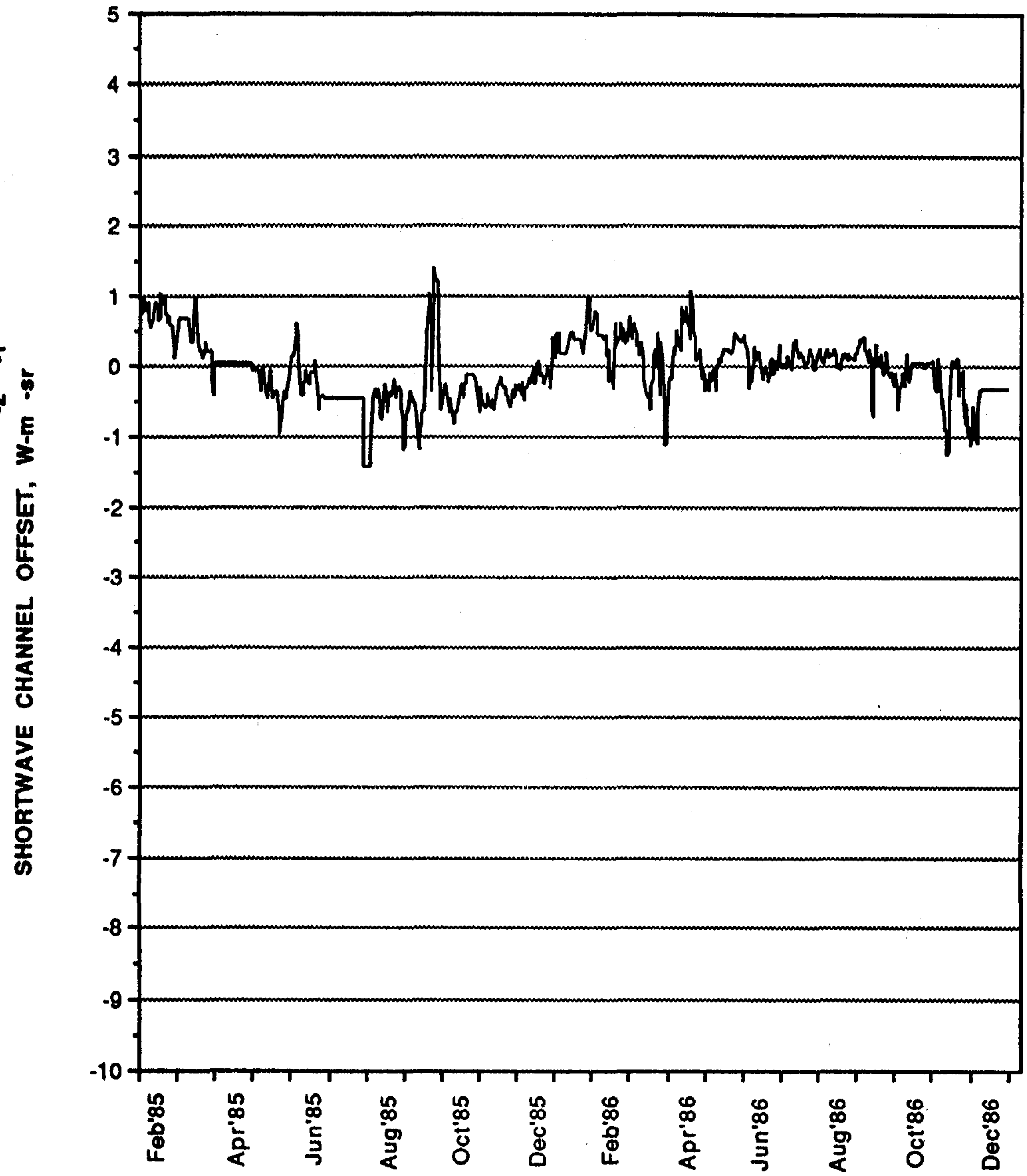

FIGURE 8.- NOAA-9 SHORTWAVE CHANNEL UNFILTERED OFFSETS NEAR THE NADIR SCAN POSITION

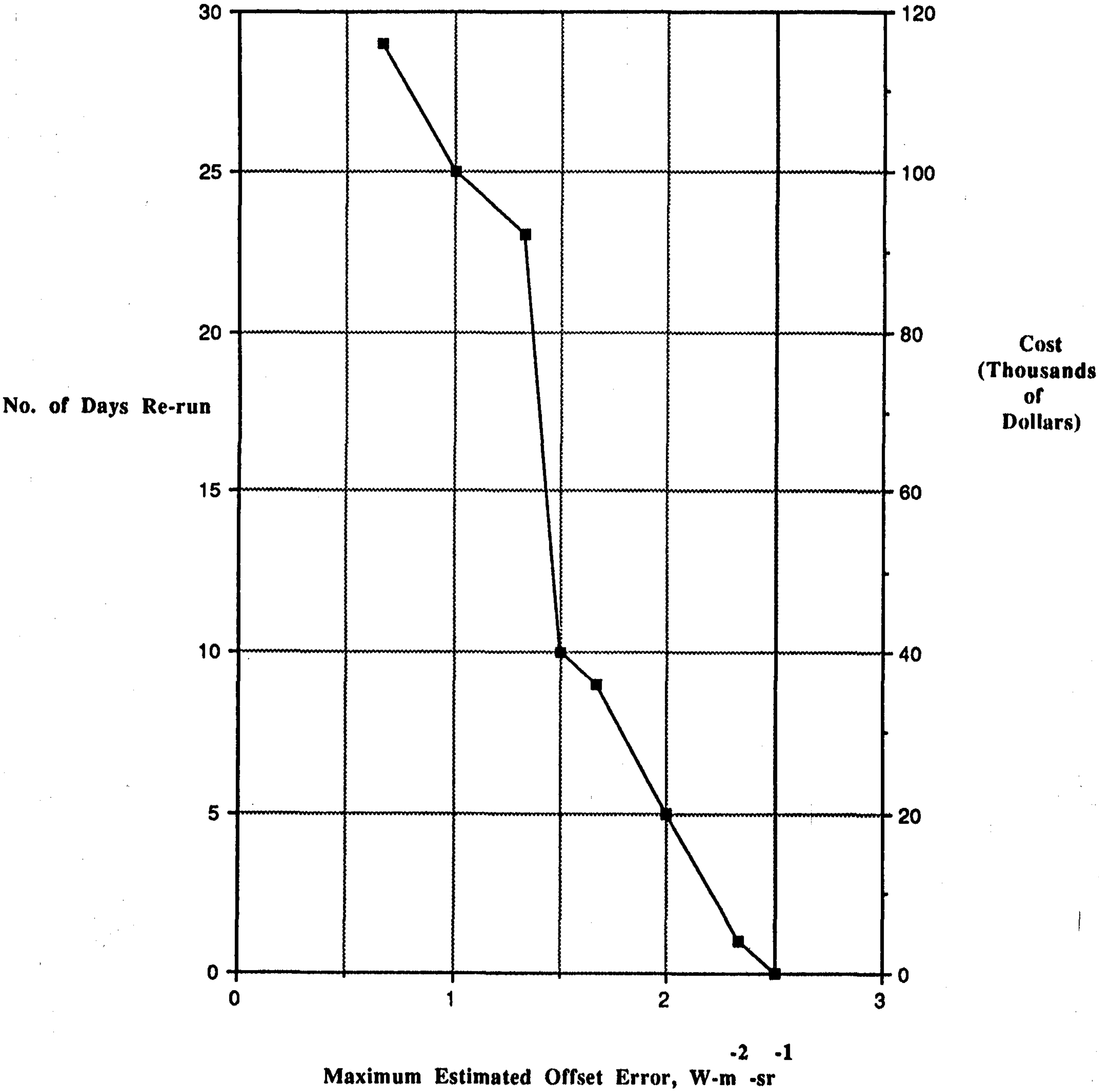

Figure 9.- NOAA-9 December 1986
Offset Accuracy / Expense Trade-Off

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13. ABSTRACT *(Maximum 200 words)*
The Earth Radiation Budget Experiment (ERBE) instruments are designed to measure the components of the radiative exchange between the Sun, Earth and space. ERBE is comprised of three spacecraft, each carrying a nearly identical set of radiometers: a three-channel narrow-field-of-view scanner, a two-channel wide-field-of-view (limb-to-limb) non-scanning radiometer, a two-channel medium field-of-view (1000 km) non-scanning radiometer, and a solar monitor. Ground testing showed the scanners to be susceptible to self-generated and externally generated electromagnetic noise. This paper describes the pre-launch corrective measures taken and the post-launch corrections to the NOAA-9 scanner data. The NOAA-9 scanner has met the mission objectives in accuracy and precision, in part because of the pre-launch reductions of and post-launch data corrections for the electromagnetic noise.

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